PREDICTION OF CHAMBER PRESSURE FOR A MACH 4 SUPERSONIC WIND TUNNEL

Z.T. Deng, Xiaoqing Qian and Dave Pett, Alabama A&M University; Dan Rodgerson, AeroLab LLC

Abstract

A variable-Mach-number supersonic wind tunnel capable of producing up to Mach 4 with a 6”x6” test section was installed at Alabama A&M University. This wind tunnel is a blow-down type which requires the compressed air to be provided through large external tanks. The compressed air is delivered to the test section through large-diameter high-pressure pipes with control valves. The test section Mach number is controlled by a variable throat area using two solid nozzle blocks with the lower nozzle block movable in the flow direction with respect to the upper nozzle block. The air is then discharged at ambient air pressure through a vertical exhaust pipe. One of the critical operational parameters is the chamber pressure. To reach steady supersonic speeds in the test section, chamber pressure has to be high enough to push out the starting shockwaves in the tunnel. Parametric studies using computational fluid dynamics simulations were conducted for a series of chamber pressures and nozzle throat areas (area ratios). Results indicated that it is very difficult to reach Mach 3.5 to Mach 4 test conditions if chamber pressure is below 120psi. In order to obtain a shockwave-free (clean) supersonic test section with a Mach number ranging from 3.5 to 4.0, it is recommended that the optimum chamber pressure be about 170psi.

Introduction

The variable-Mach-number supersonic wind tunnel at Alabama A&M University (AAMU) is of the blow-down type. It was designed and manufactured by AEROLAB [1]. The air is compressed through an external compressor and is then stored in three large air tanks. The wind tunnel compressed air system is installed on a 1,200ft² concrete pad. The compressed-air system provides one thousand cubic feet (7,500 gal.) of dry air at 200psi. The system is designed to charge three storage/discharge tanks from atmospheric pressure (~14.7psi) to 200psi in less than one hour in order to accommodate rapid-turn-around test sequences. The tanks are capable of combined or individual discharge. Isolation valves are installed between the storage/discharge tanks and all components in the system for isolation of operation, maintenance and repair. Figure 1 shows the compressed-air supply system. The high-pressure, room-temperature air is then discharged through a large-diameter, high-pressure pipe and inlet diffuser to a mixing chamber and to create an air supply to the supersonic wind tunnel. The high-pressure air is then accelerated through a converging-diverging nozzle to provide Mach 4 speed at the inlet of the test section. The inlet of the test section is 6”x6” square. The converging-diverging nozzle upstream of the test section inlet has a variable throat area in order to provide supersonic flows with variable-test-section inlet Mach number. The air is then discharged at subsonic speeds and enters a large-diameter vertical exhaust pipe at ambient pressures. Figure 2 shows the supersonic wind tunnel system.

Figure 1. External Compressed-Air Supply System

Figure 2. Supersonic Wind Tunnel System at AAMU

The inlet valve and nozzle block are processor controlled. An electromechanical inlet valve controls inlet air pressure.

The valve automatically terminates the test run when inlet pressure falls to within 10psi of the required inlet chamber pressure. A stagnation tank containing baffle plates and turbulence-reducing screens conditions inlet air. The establishment of the critical chamber pressure is crucial to the success of the tunnel operation.

The wind tunnel employs a sliding-nozzle-block design with the lower block adjustable in position with respect to the upper block, as shown in Figure 3.

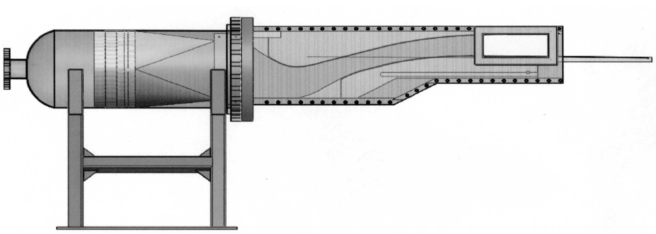


Figure 3. Moving Lower Nozzle Block

Nozzle contours are electrically adjusted through a linear actuator, as shown in Figure 4. Adjusting the lower nozzle block will change nozzle throat diameter and, in turn, change the test-volume-inlet Mach number. The sliding block design provides a continuous Mach number between 1.3 and 4.

Figure 4. Control of the Lower Nozzle Block Through a Linear Actuator

The design test Mach number ranges from 1.3 to 4.0. The wind tunnel test section and observation windows have fixed inlet dimensions of 6"W x 6"H x 18"L, as shown in Figure 5. According to isentropic theory [2], the test-volume-inlet Mach number can be determined solely based on the area ratio between nozzle exit and nozzle throat. However, the starting process of the supersonic wind tunnel requires high power to overcome the normal shock loss [3] and, in general, the higher the test Mach number, the higher the power requirement. This power requirement can be interpreted as the ratio of the necessary stagnation pressure to diffusor exit ambient pressure. With the normal shock in the test section, the theoretical compression ratio between stagnation chamber pressure and diffusor exit pressure ranges from 1 to approximately 7.5 for testing Mach numbers between 1 and 4 [3]. The probable maximum needed for starting of supersonic wind tunnel at Mach 4 is approximately 15, which is equivalent to a pressure of 220psi with respect to standard air exhaust. When flow becomes steady, the probable minimum needed for running the tunnel at Mach 4 is about 6. In practice, the parameters affecting the test-volume Mach number are throat area, chamber pressure, flow quality and starting, and back pressure [4-8]. The Mach number at the test-section inlet of the supersonic wind tunnel is locked by the area ratio once supersonic flow is established in the test section. If chamber pressure increases above the minimum required pressure, the test-section Mach number will not change. However, if the chamber pressure is low enough, the normal shockwave may not be pushed out of the test section and a clean supersonic flow may not be established at the desired area ratio. The objective of this study was to numerically predict the minimum operational chamber pressure requirement for AAMU's Mach 4 supersonic wind tunnel, under different test-volume Mach numbers.

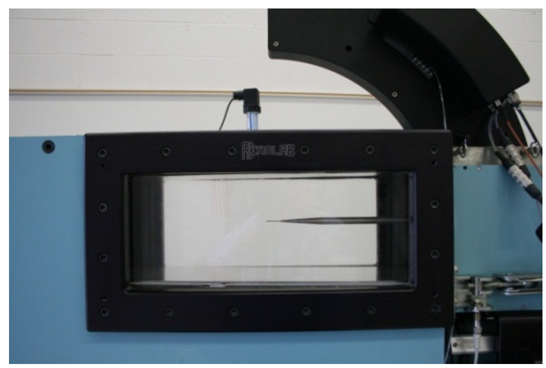


Figure 5. 6"x6"x18" Test Volume and Observation Window

Numerical Procedures

The ideal test-volume-inlet Mach number can be calculated based on isentropic theory using area ratio, as in Figure 6. It is possible to reach Mach 4 speed with an area ratio close to 11. But, with viscous effects, the ideal prediction does not provide an accurate prediction of Mach number for the supersonic wind tunnel. The full Navier-Stokes equations must be solved for the entire flow field in order to obtain realistic test-volume flow characteristics.

In the current study, computational fluid dynamics (CFD) simulations were conducted using WIND code [9]. This CFD tool solves Reynolds-Averaged Full Navier-Stokes (RANS) equations with conventional laminar or turbulent models. It was observed that the prediction of the test-volume Mach number depends on specification of downstream conditions for both Laminar and turbulent-flow simulation models. To select appropriate flow model and boundary conditions, a series of one-zone simulations were conducted. In these calculations, air was discharged at ambient pressures from the diffusor exit. As indicated in Figure 7(a-c), various exit boundary conditions were applied with Laminar and/or turbulent-flow assumptions. Boundary layers were very thick and flow separation inside the diffuser was obvious.

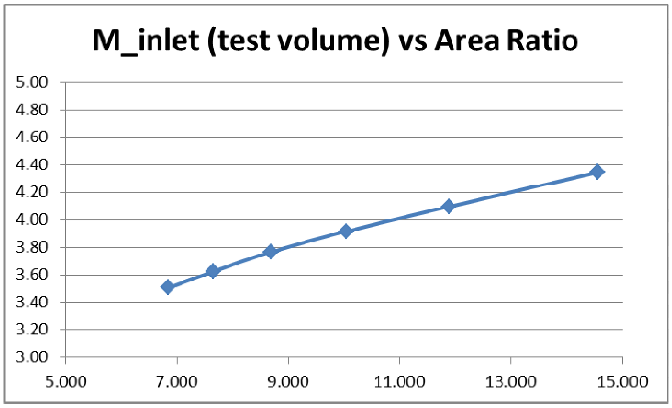


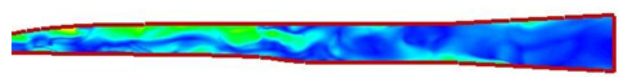
Figure 6. Ideal Design Mach Number at the Inlet of Test Volume as a Function of Area Ratio

It was observed that if downstream boundary conditions were relaxed to be pure extrapolation of pressure, a complete supersonic expansion was obtained, as indicated in Figure 7(d), even in the downstream diffuser section causing exit pressure to be near vacuum. This un-realistic condition cannot be achieved in the experiment at room condition laboratory. This suggested that conventional boundary conditions may not be accurate if the vertical exhaust-pipe configuration is neglected. A realistic vertical pipe configuration has to be considered. Multi-zone computation is needed. Apparently, the selection of a laminar model inside the diffuser section created inaccurate Mach number distributions. It was observed that the turbulent models used in the prediction play important roles in controlling wall boundary layers. A suitable turbulent model inside the wind tunnel must be selected for the simulation. Extensive simulation was performed in order to select a valid turbulent model. The turbulent models used in the prediction play important roles in controlling wall boundary layer growth. It was concluded that the Spalart turbulent model was good for the present flow simulation using the existing RANS solver.

Results and Discussion

The two-zone computational domain was created to compute air flow from the inlet of the stagnation settling chamber to the vertical exhaust pipe exit. Figure 8 shows zone 1 of the computational domain covering flows from the inlet to the diffusor exit of the wind tunnel. According to the theoretical prediction [2], if the ambient pressure is the standard 14.7psi, the operational chamber pressure should then range from 110 to 220psi in order to reach Mach 3-4 test conditions. As a result of this, a group of representative chamber pressures of 180, 160 and 120psi were selected for the CFD simulation. The pressure at the vertical exhaust pipe exit was considered to be standard air and fixed at 14.7psi. The area ratio was computed as the ratio of test-volume inlet to nozzle throat. The area ratio between test-volume inlet and control-nozzle throat were selected from 6.8 to 14.6, according to the wind tunnel configurations. The corresponding test Mach number ranged from 3.5 to 4.0. Table 1 shows the simulation parameter matrix in terms of chamber pressure and area ratio. It was extracted from relative positions between upper and lower nozzle blocks based on the CAD geometry. A combination of 18 simulation cases were conducted.

(a) Constant Back Pressure Ratio of 0.044



(b) Constant Back Pressure Ratio of 0.031

(c) Constant Back Pressure Ratio of 0.006

(d) Extrapolation Exit Boundary
(Cannot be achieved on experimental setting)

Figure 7. Effects of Downstream Conditions on the Simulation

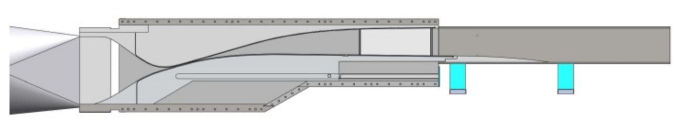
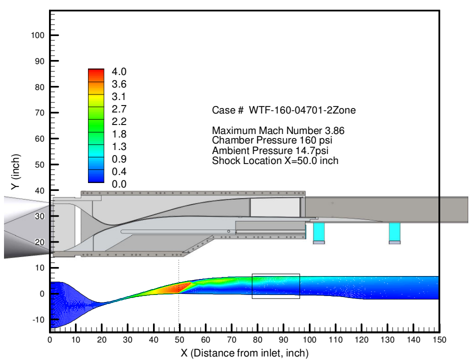


Figure 8. Sketch of the Flow Path of the AAMU Mach 4 Supersonic Wind Tunnel

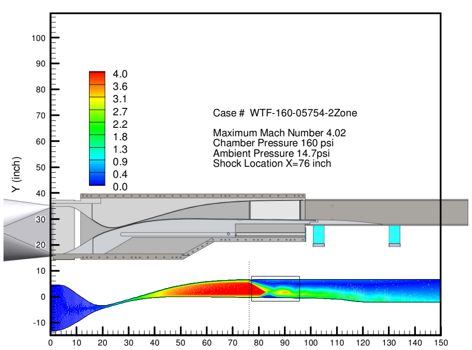
Table 1. CFD Simulation Parameter Matrix

Area Ratio	Chamber Pressure (psi) / Ambient Pressure (psi)		
14.6	180 / 14.7	160 / 14.7	120 / 14.7
11.9	180 / 14.7	160 / 14.7	120 / 14.7
10.0	180 / 14.7	160 / 14.7	120 / 14.7
8.7	180 / 14.7	160 / 14.7	120 / 14.7
7.7	180 / 14.7	160 / 14.7	120 / 14.7
6.8	180 / 14.7	160 / 14.7	120 / 14.7

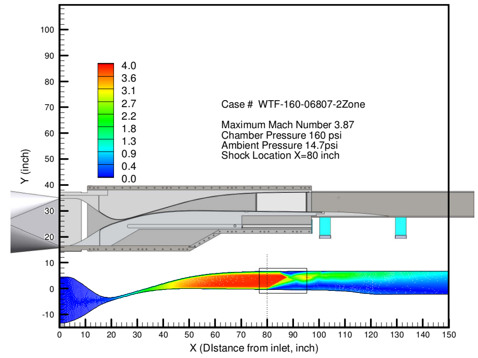
Figure 9 (a-f) shows the computational results at a chamber pressure of 160psi and a back pressure of 14.7psi. Six lower-nozzle block positions were used to compute the area ratio, as indicated in Table 1. At larger throat areas, the maximum Mach number in the test section reached 3.56; at the same time, shockwaves existed in the downstream diffusor, while the test volume was shock-free. As the throat area decreased, the maximum test Mach number in the test volume increased; however, the shockwave approached closer and closer to the test volume from downstream. As area ratio decreased to 8.7, the maximum Mach number reached 3.87, but shockwaves existed inside the test volume.



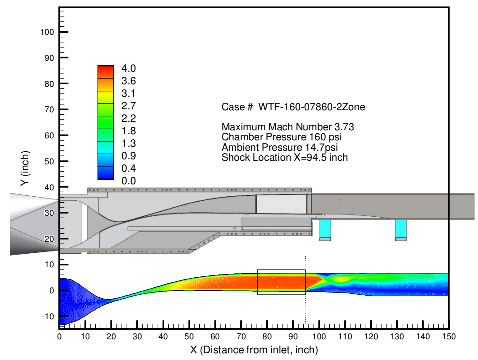
(a)



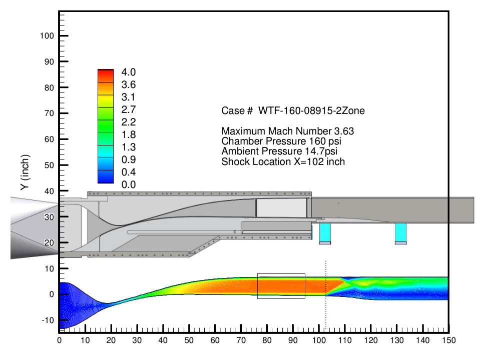
(b)



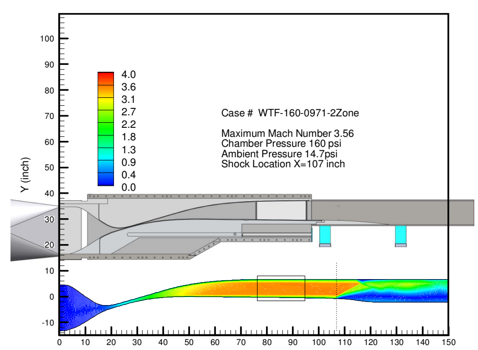
(c)



(d)



(e)

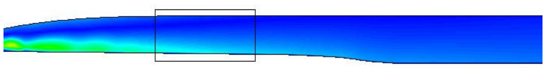


(f)

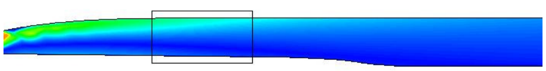
Figure 9 (a-f). Mach Number Contours and Shockwave Locations Inside the Test Volume for Case 160 / 14.7

Further reduction of area ratio created shockwaves inside the test volume. When area ratio reached 6.8, the minimum throat opening was reached and it was obvious that viscous effects become dominant and the entire test-volume Mach number was below 2.7.

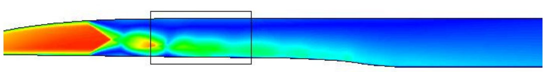
Figure 10 shows the CFD simulation results for test-volume Mach number distribution and shockwave location near the test volume for the cases 120/14.7 (a1-a6) and 180/14.7 (b1-b6) for the selected area ratio. Measured from the wind tunnel design geometry CAD file, the test-section observation window started at 76 inches from the settling chamber exit. At a chamber pressure of 120psi, it was seen that shockwaves exist inside the test volume. In order to get a clean test volume, the shockwave has to be pushed out of the test volume for all area ratios. This suggests that in order to obtain Mach 3.5 to 4.0 test Mach numbers, the minimum chamber pressure should be higher than 120psi. If chamber pressure cannot be increased, then back pressure has to be lowered.



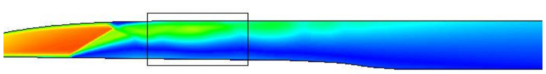
(a1)



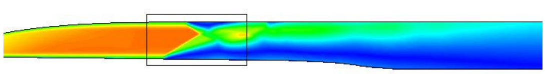
(a2)



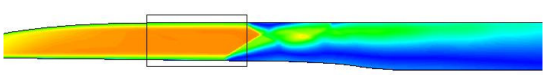
(a3)



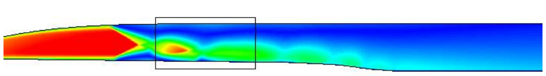
(a4)



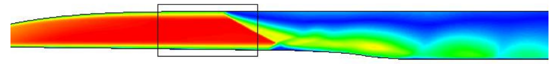
(a5)



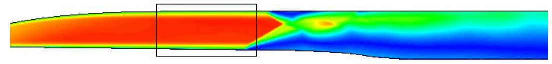
(a6)



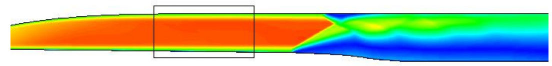
(b1)



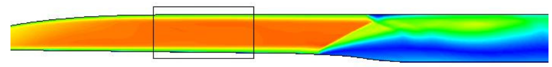
(b2)



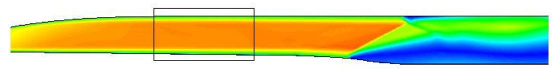
(b3)



(b4)



(b5)



(b6)

Figure 10. Mach Number Distribution and Shockwave Location Near the Test Volume: a1-a6 Pressure Ratio 120psi Chamber / 14.7psi Back; b1-b6 Pressure Ratio of 180psi Chamber / 14.7psi Back. Area Ratio Index (1) 14.6; (2) 11.9; (3) 10.0; (2) 8.7; (5) 7.7; (6) 6.8

With the wind tunnel suggested geometry, it was found that area ratio 10 (case index 3) with a chamber pressure of 180psi will comfortably provide Mach 4 test-volume conditions. Figure 11 summarizes the maximum Mach number reached for a given chamber pressure and area ratio. Figure 12 shows the shockwave locations. Results indicated that under chamber pressures of 160 and 180psi, the wind tunnel will produce clean supersonic test conditions up to Mach 3.85 at area ratios smaller than 10. To reach Mach 4 test conditions, it is necessary to raise the chamber pressure above 160psi in order to create clean supersonic test condition inside the test volume. At 180psi chamber pressure, it is possible to reach Mach 4 at an area ratio of 10. Therefore, it is recommended that the optimum chamber pressure for Mach 3.5 to 4.0 tests is approximately 170psi, if back pressure at the vertical pipe exit is 14.7psi. It is very difficult to obtain Mach 4 test conditions if chamber pressure is below 120psi.

Conclusion

CFD simulations were conducted to predict critical settling chamber pressure requirements for AAMU's Mach 4 supersonic wind tunnel. The CFD simulation adopts RANS solver of Navier-Stokes equations with the Spalart turbulent model. Real wind-tunnel geometry was used to construct a computational domain. Results indicated that it is very difficult to reach Mach 3.5 to Mach 4 test conditions if chamber pressure is below 120psi. In order to obtain a shockwave-free (clean) supersonic test section between Mach 3.5 and 4.0, it is recommended that the optimum chamber pressure be about 170psi.

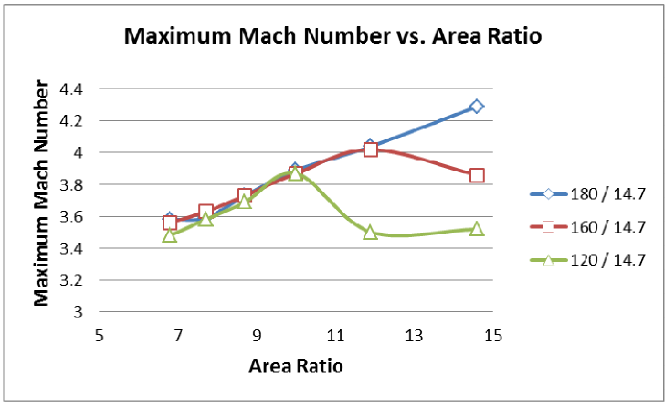


Figure 11. Computed Maximum Test Volume Mach Number as a Function of Area Ratio

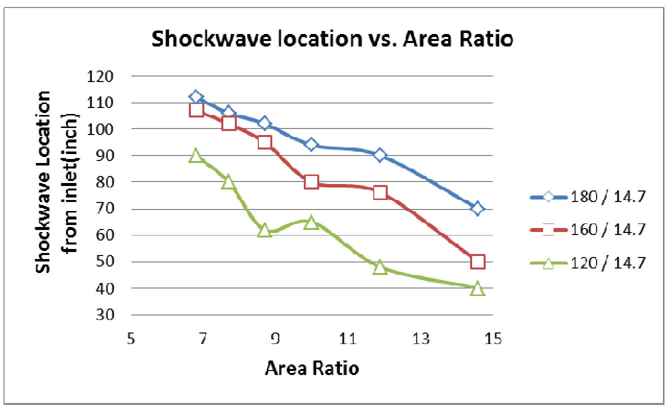


Figure 12. Computed Shockwave Location Measured from the Chamber Exit

References

[1] AeroLab. (2011, April). *6-inch Variable Mach Number Supersonic Wind Tunnel System, Operator's/ Owner's Manual*. (Volume 1.1). Alabama A&M University.

[2] Zuker, R. D., & Biblarz, O. (2002). *Fundamentals of Gas Dynamics*. (2nd ed.). John Wiley.

[3] Pope, A., & Goin, K. L. (1965). *High-Speed Wind Tunnel Testing*. John Wiley & Sons.

[4] Braun, E., Lu, F., Panicker, P., Mitchell, R., Wilson, D., et al. (2008). Supersonic Blowdown Wind Tunnel Control Using LabVIEW. *46th AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2008-852*.

[5] Mittal, S., & Yadav, S. (2001). Computation of Flows in Supersonic Wind-Tunnels. *Computer Methods in Applied Mechanics and Engineering*, *191*, 611 -634.

[6] Squire, L.C. (1998). A Review of the Role of Some Small High-Speed Wind Tunnels in Aeronautical Research. *Prog. Aerospace Science*, *34*, 107-166.

[7] Rao, M., Collier, A. S., & Hand, T. (2006). Design and Manufacture of the AEDC Tunnel 9 Aerodynamic Mach 8 Nozzle. *25th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, AIAA-2006-2812*.

[8] Mitchell, R., & Lu, F. (2009). Development of a Supersonic Aerodynamic Test Section Using Computational Modeling. *39th AIAA Fluid Dynamics Conference, AIAA-2009-3573*.

[9] The NPARC Alliance. (2008). *Wind-US User's Guide, version 2*. NASA Glenn Research Center & USAF Arnold Engineering Development Center.

Biographies

Z.T. DENG is a professor in Mechanical Engineering at the Alabama A&M University. Dr. Deng may be reached at zhengtao.deng@aamu.edu.

XIAOQING QIAN is a professor in Mechanical Engineering at the Alabama A&M University.

DAVE PETT is an engineer in the college of engineering, technology and physical science at Alabama A&M University.

DAN RODGERSON is the general manager of Aerolab LLC, in Laurel, Maryland.